Aerodynamic Performance of a Compact, High Work-Factor Centrifugal Compressor at the Stage and Subcomponent Level

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- Background and Scope
- Test Article and Facility Description
- Key Instrumentation
- Stage and Subcomponent Results
- Performance Assessment vs. Pre-test CFD
- Summary

Background and Scope

- **NASA/UTRC High Efficiency Centrifugal Compressor (HECC)** NRA cost-share contract
  - Develop HPC technologies for advanced turboshaft engines for rotorcraft
  - Challenging goal set for centrifugal compressors
  - Maintain similitude between engine scale and rig scale hardware
  - Design/Analysis, fab, assembly, test

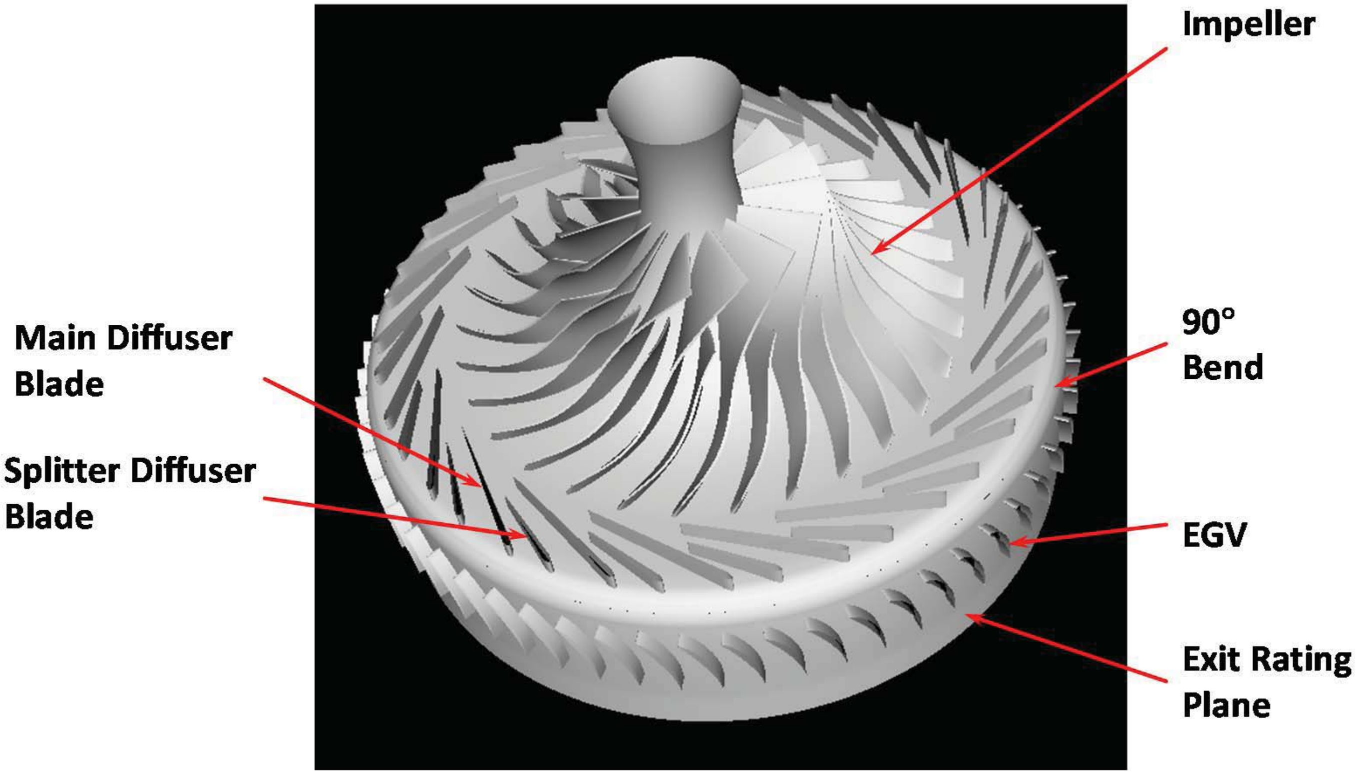
Metric	**Intent (rig scale, 2x engine scale)**	**CFD***
Exit-corr. flow	$2.1 < \dot{m}_{c,ex} < 3.1\ lb_m/s$	2.98
Work factor	$0.60 < \Delta H_0/U^2_2 < 0.75$	0.7905
$\eta_{p,tt}$ (poly)	≥ 0.88	0.888
Diam. ratio	$D_{max} / D_2 \leq 1.45$	1.45
Design SM	13%	12%
M_{ex}	0.15	0.15
α_{ex}	15º	14º

*Medic, G., et al., “High Efficiency Centrifugal Compressor for Rotorcraft Applications,” NASA/CR—2014-218114, Sept., 2014.

HECC Stage Overview

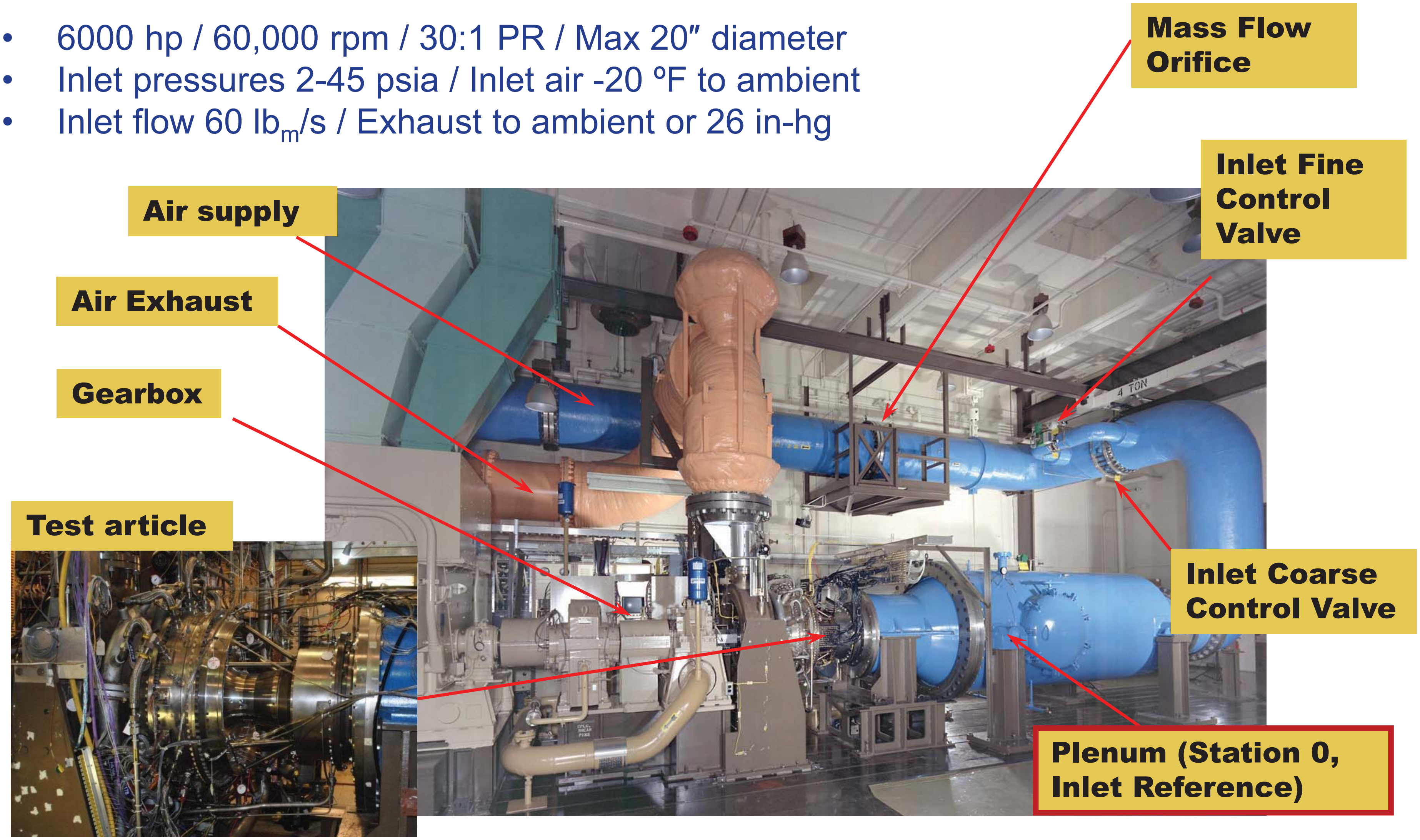
Design speed = 21,789 ft/s (Exit tip speed = 1615 ft/s)

- **Impeller**: 15 blade/splitter pairs, spanwise varying backsweep, lean, elliptical leading and trailing edges
- **Diffuser**: 20 vane/splitter pairs, with splitters offset to maximize pressure recovery
- **EGVs**: 60 cascade-style airfoils

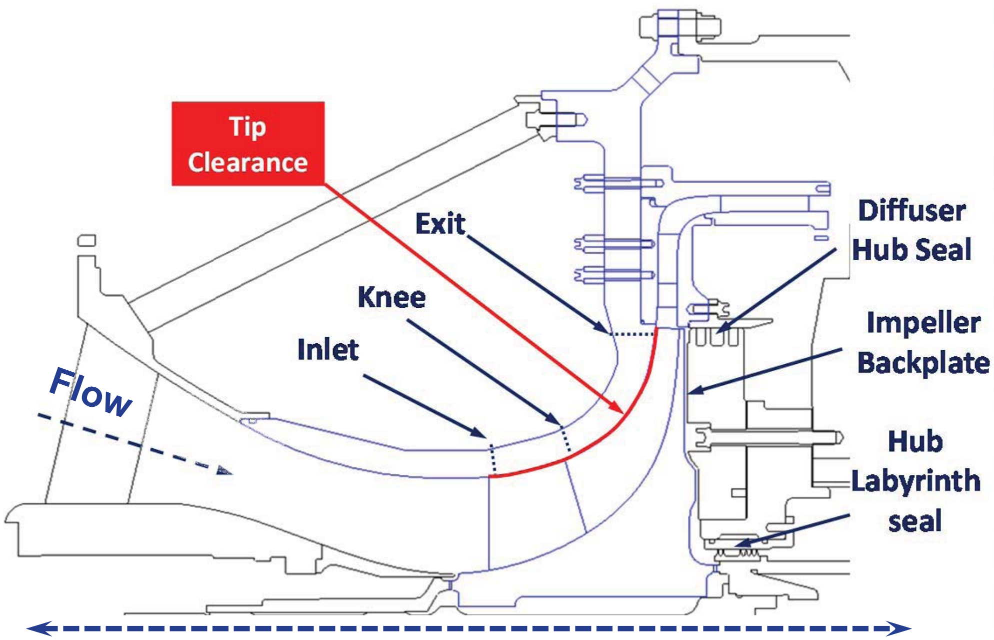


Small Engine Component Test Facility (CE-18)

- 6000 hp / 60,000 rpm / 30:1 PR / Max 20″ diameter
- Inlet pressures 2-45 psia / Inlet air -20 ºF to ambient
- Inlet flow 60 lb_m/s / Exhaust to ambient or 26 in-hg



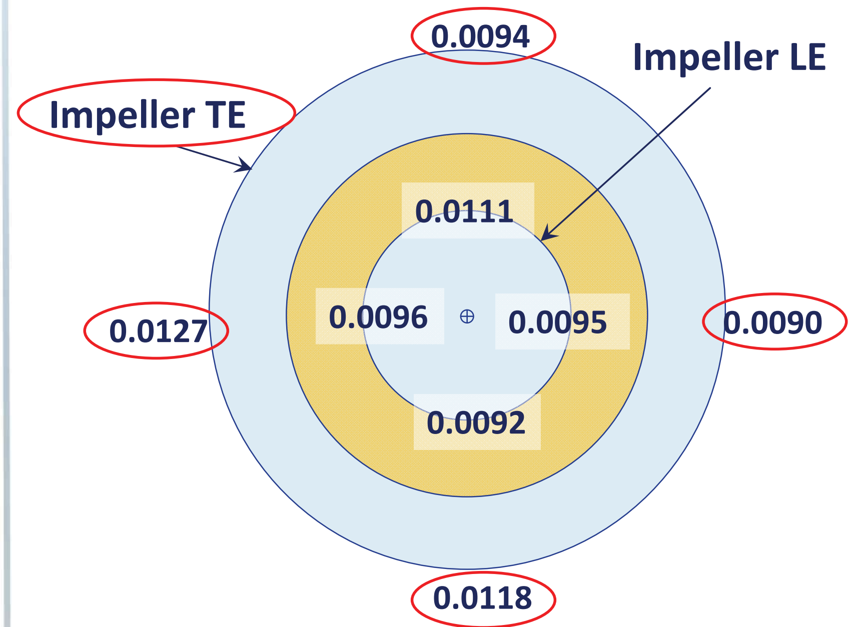
Tip Clearance System



Impeller Translates Axially

- 4 rub probes at each station used for tip clearance calibration/alignment
- ε/b = 2% (0.012″) design tip clearance, no step in flowpath at impeller/diffuser interface

Tip Clearance Variations @ N_c = 100%

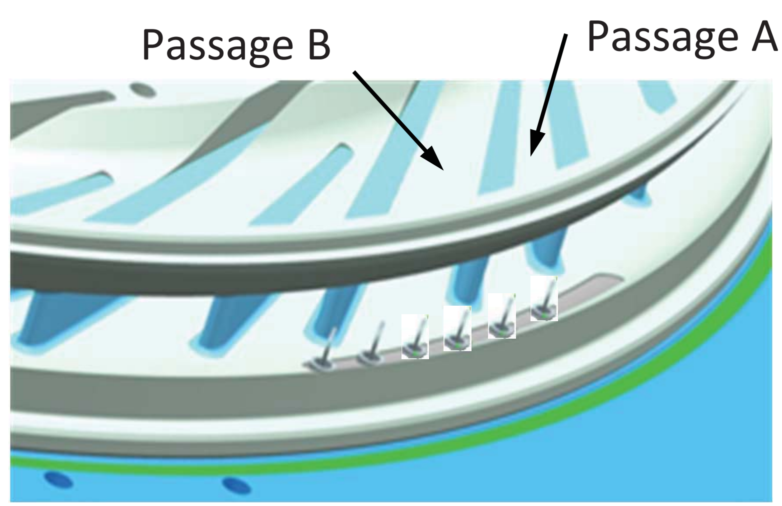


$\Delta\varepsilon/b$ *of* 0.5%, → 0.12 pt. impact on η_{tt}

Diffuser LE and "Rake" Instrumentation

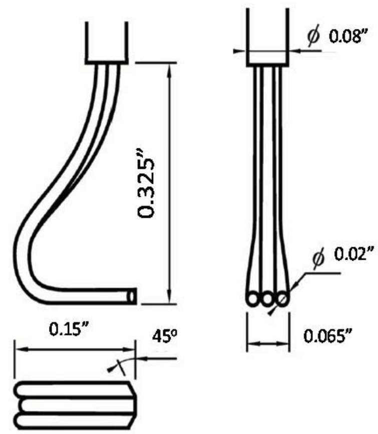
- Vane Leading Edge (2.4)
  - Two vanes with 7 Kiel head p_0 ports
  - Key measurements for impeller and diffuser performance

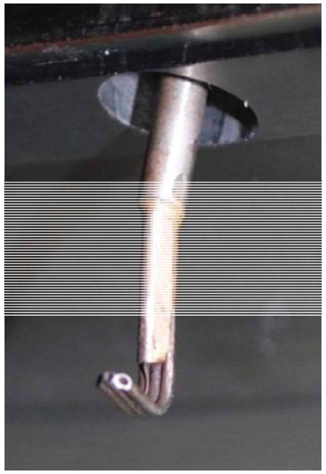
- Vane Trailing Edge (2.7)
  - 6 locations resolve one main-to-main diffuser passage
  - Miniature Cobras at immersions of 15-85%, calibrated for α and p_0

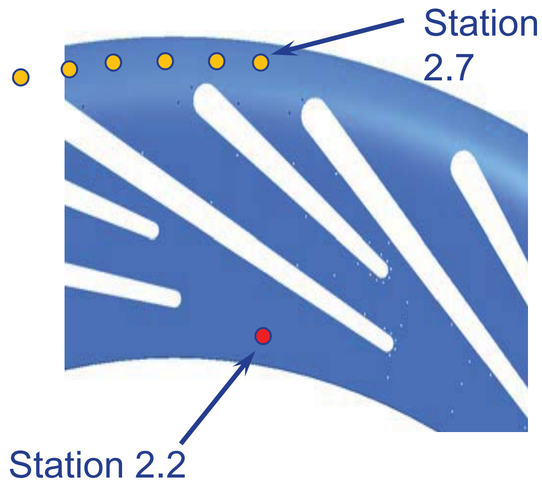


Surveys
3-Port Cobra Probe

- Vaneless Space (2.2) & Diffuser Exit (2.7)
  - Traversable spanwise, manually aligned to flow
  - Calibrated to M=0.84 (Cal. Facility limit)

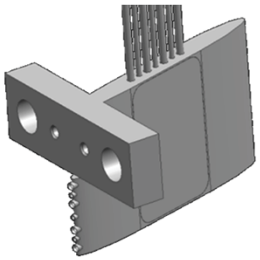






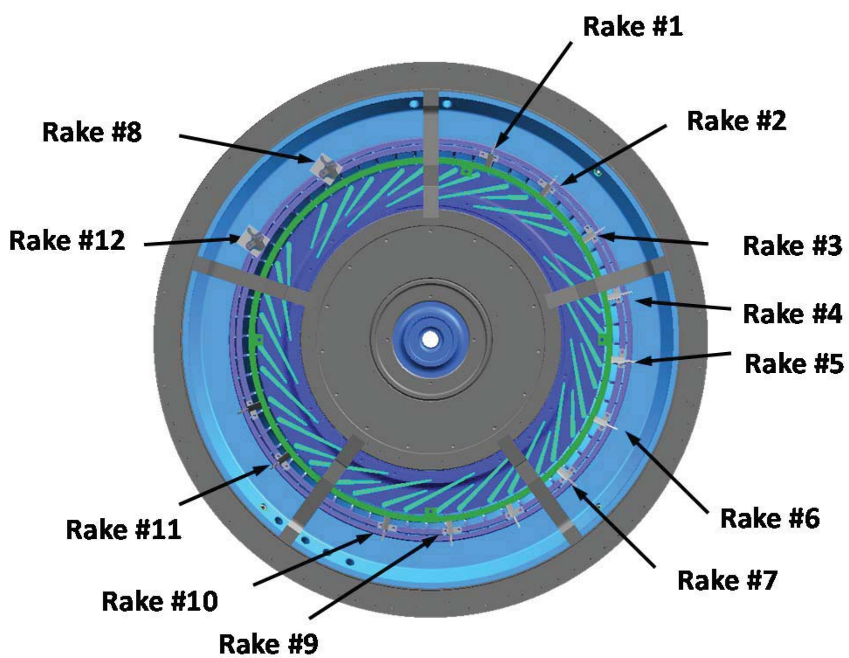
EGV Exit/Stage Rating (Station 3)

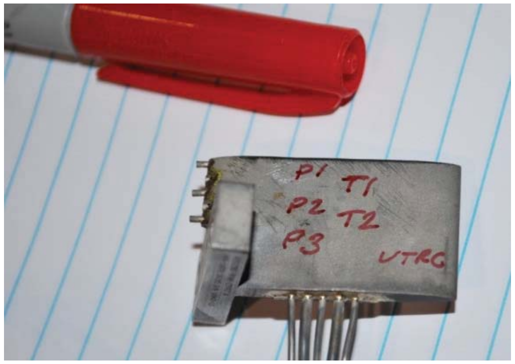
- 12 Rakes indexed to resolve one main-to-main diffuser pitch
- Kiel head p_0 and T_0 ports on area centroids
- 3 adjacent EGVs have LE Kiel head p_0 (25-75% span)



p_o x3

T_o x2

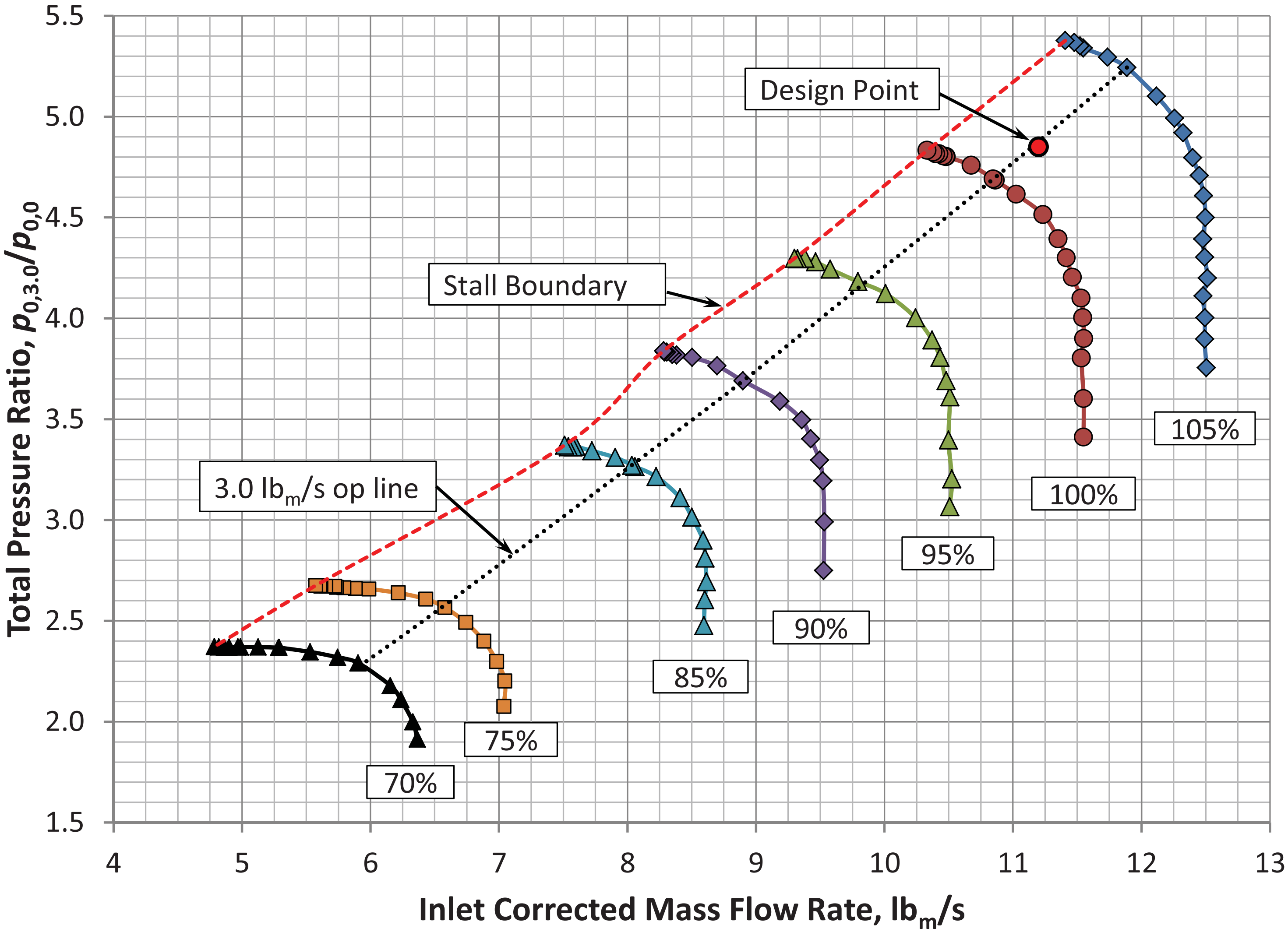




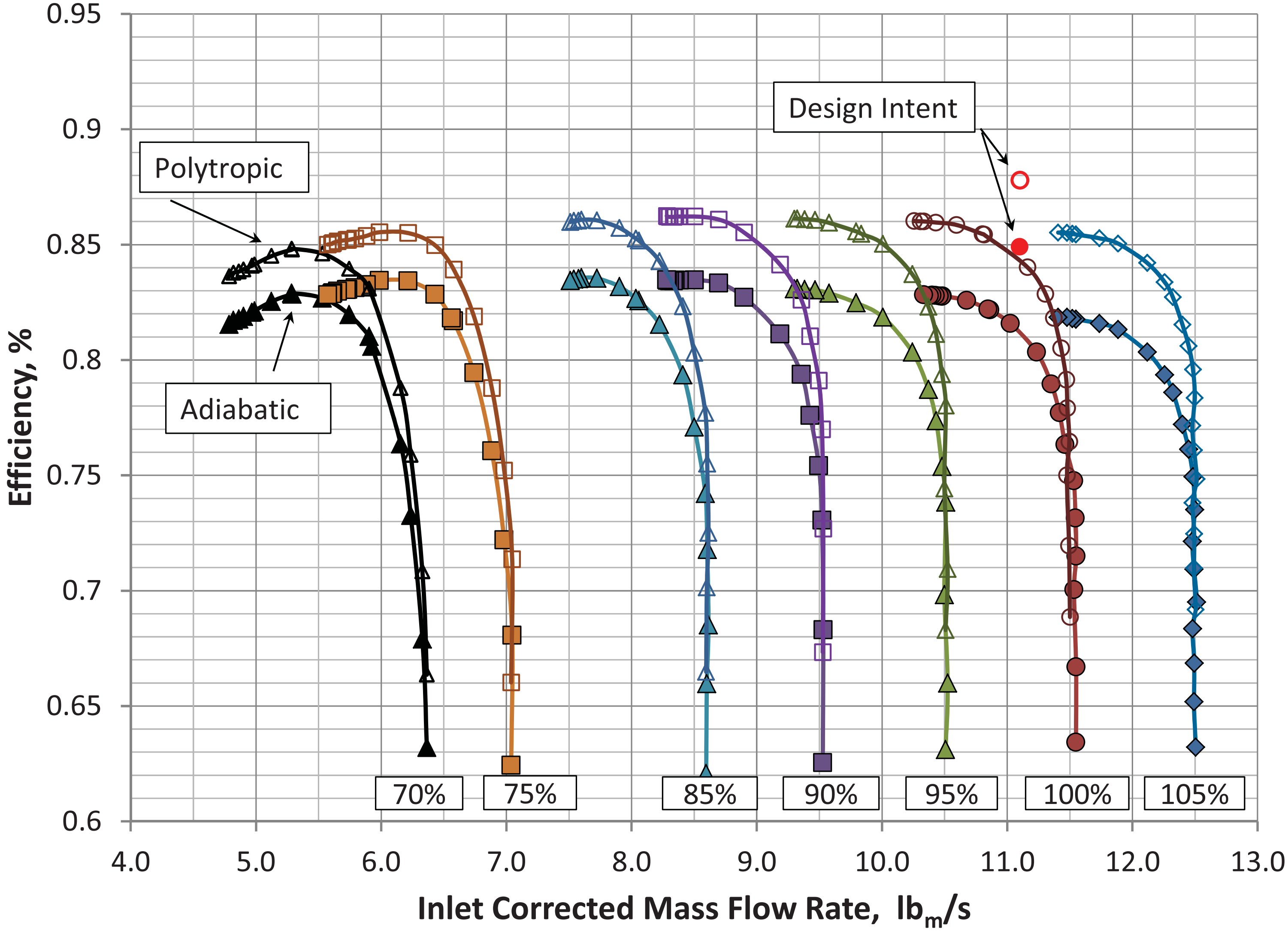
Stage and Subcomponent Results

- Compressor Maps
- Design point performance - comparison of measured vs. predicted
- Representative subcomponent measurements at N_c = 100%

Stage Pressure Ratio vs. Inlet Corrected Mass Flow Rate



Efficiency vs. Inlet Corrected Mass Flow Rate



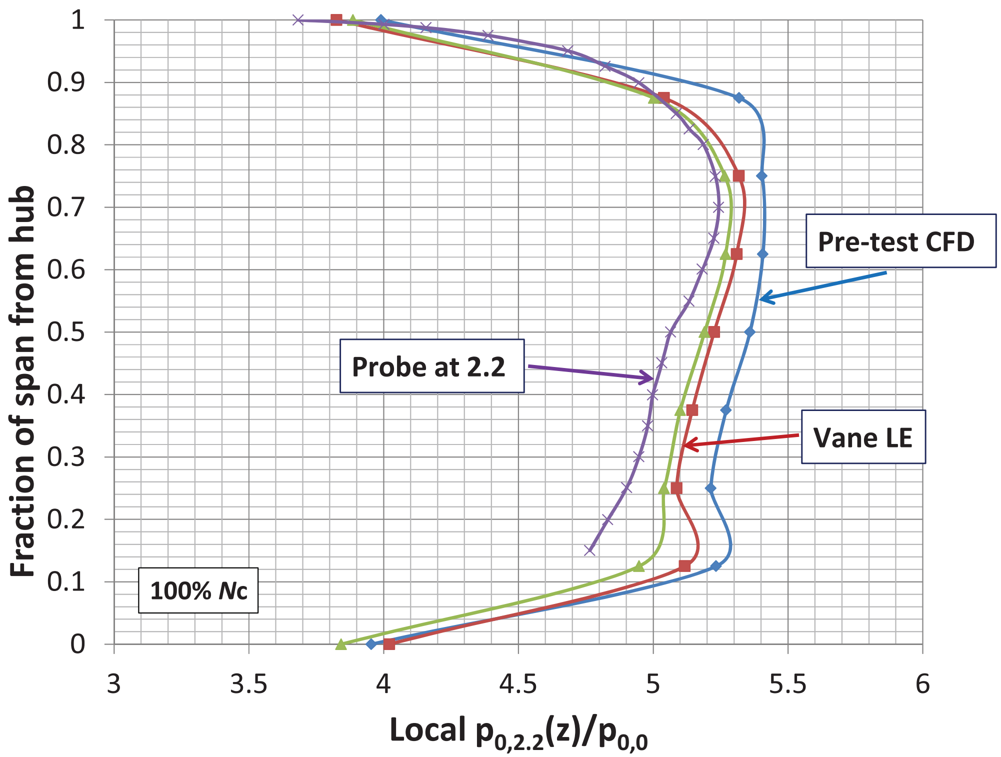
Measured vs. Predicted Performance

(N_c = 100%, $\dot{m}_{c,ex}$ = 3.0 lbm/s, design tip clearance)

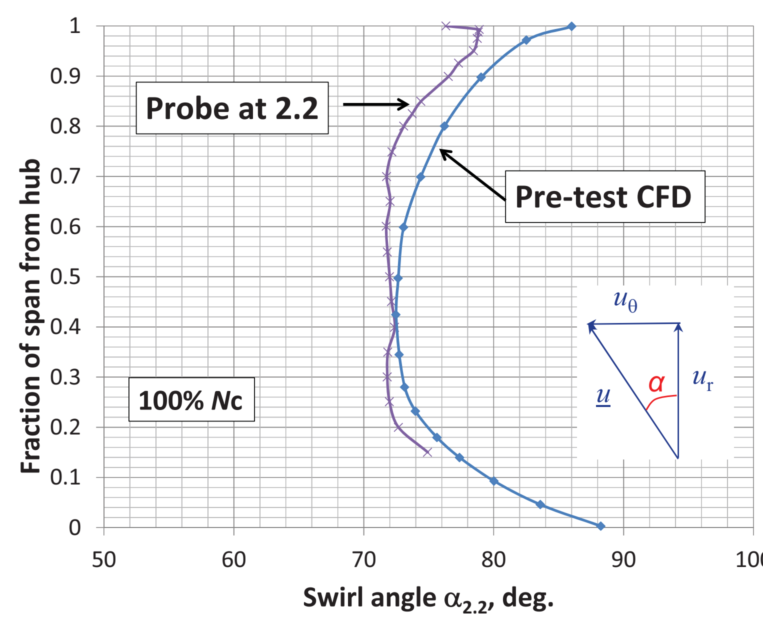
Metric	Design Goal	Rig Scale Design Intent $p_{0,0}$=14.7 psia	Rig Scale Design Intent $p_{0,0}$=11 psia	Measured $p_{0,0}$=11 psia ±Uncertainty (95% Confidence)
Pressure ratio, $p_{0,3}/p_{0,0}$		4.85	4.80	4.68 ± 0.0074
Inlet flow rate, $\dot{m}_{c,in}$, lb_m/s		11.2	11.1	10.85 ± 0.1
Exit flow rate, $\dot{m}_{c,ex}$, lb_m/s	$2.1 < \dot{m}_{c,ex} < 3.1$	2.98	2.98	2.98
Adiabatic efficiency, η_{tt}, %		0.862	0.8495	0.822 ± 0.011
Polytropic efficiency, $\eta_{p,tt}$, %	≥ 0.88	0.888	0.879	0.855
Adiabatic, total pressure to static pressure, η_{ts}, %		0.852	0.8396	0.805
Exit Mach number, M_{ex}	0.15	0.15	0.15	0.18
Exit flow angle, α_{ex}, deg	15°	14°	14°	34.3°
Stability Margin, SM, %	13	12	12	7.5
Work factor	$0.60 < \Delta H_0/U_2^2 < 0.75$	0.7905	0.793	0.81
Diameter ratio	$D_{max}/D_2 \leq 1.45$	1.45	1.45	1.45

Impeller Exit (2.2) and Diffuser Vane LE (2.4)

(N_c = 100%, $\dot{m}_{c,ex}$ = 3.0 lb_m/s)



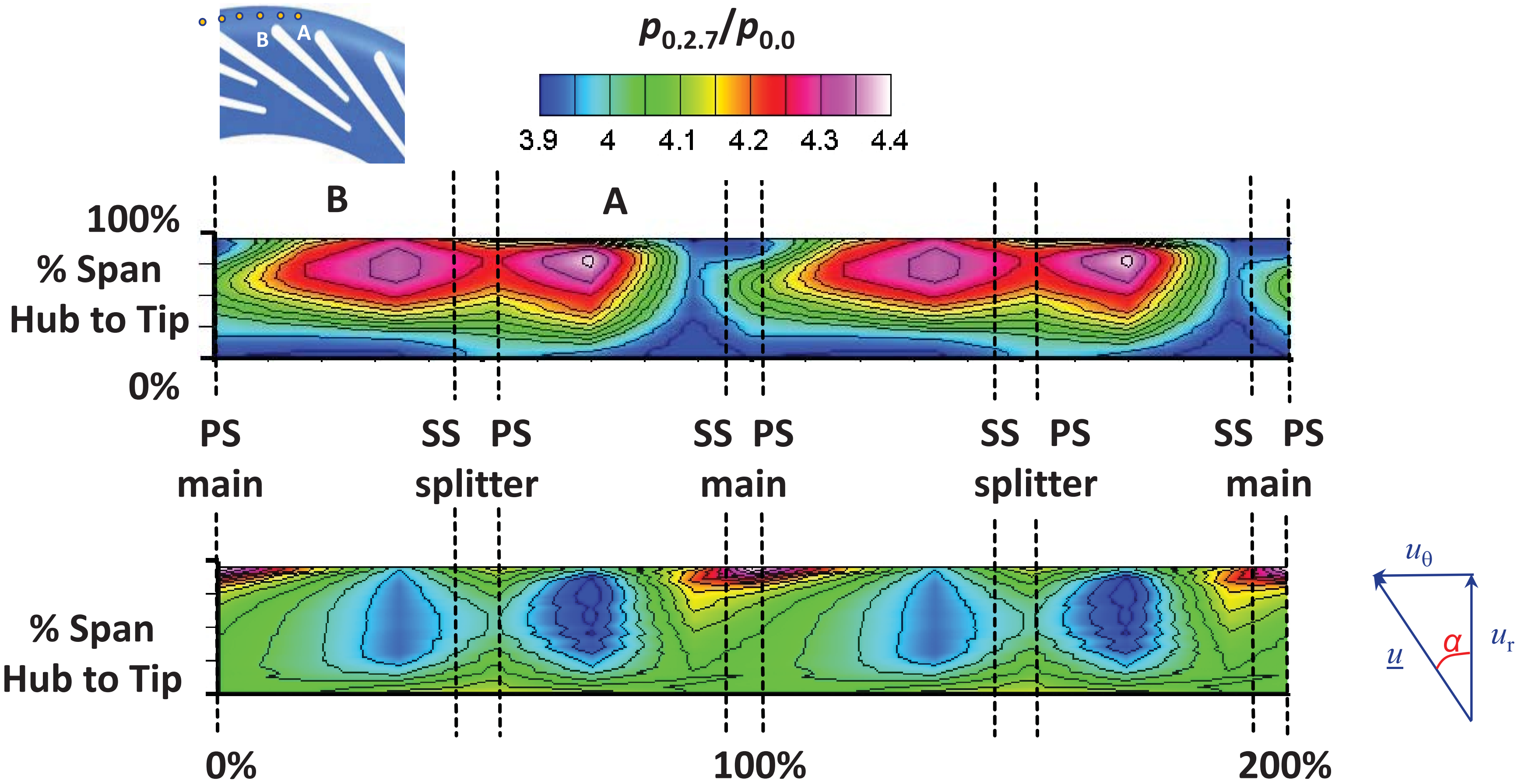
- Measured swirl angle in relatively good agreement



- Vane to vane agreement very good
- Vane LE and CFD in good agreement
- Probe p_0 (at 2.2) lower than vane LE, probe does not adequately resolve the pressure flow field
- Probe (2.2 vaneless space) data only used qualitatively

Diffuser Exit Probe Survey Data (2.7)

(N_c = 100%, $\dot{m}_{c,ex}$ = 3.0 lb_m/s)



% Pitch, Main to Main

Flow Angle, Deg.

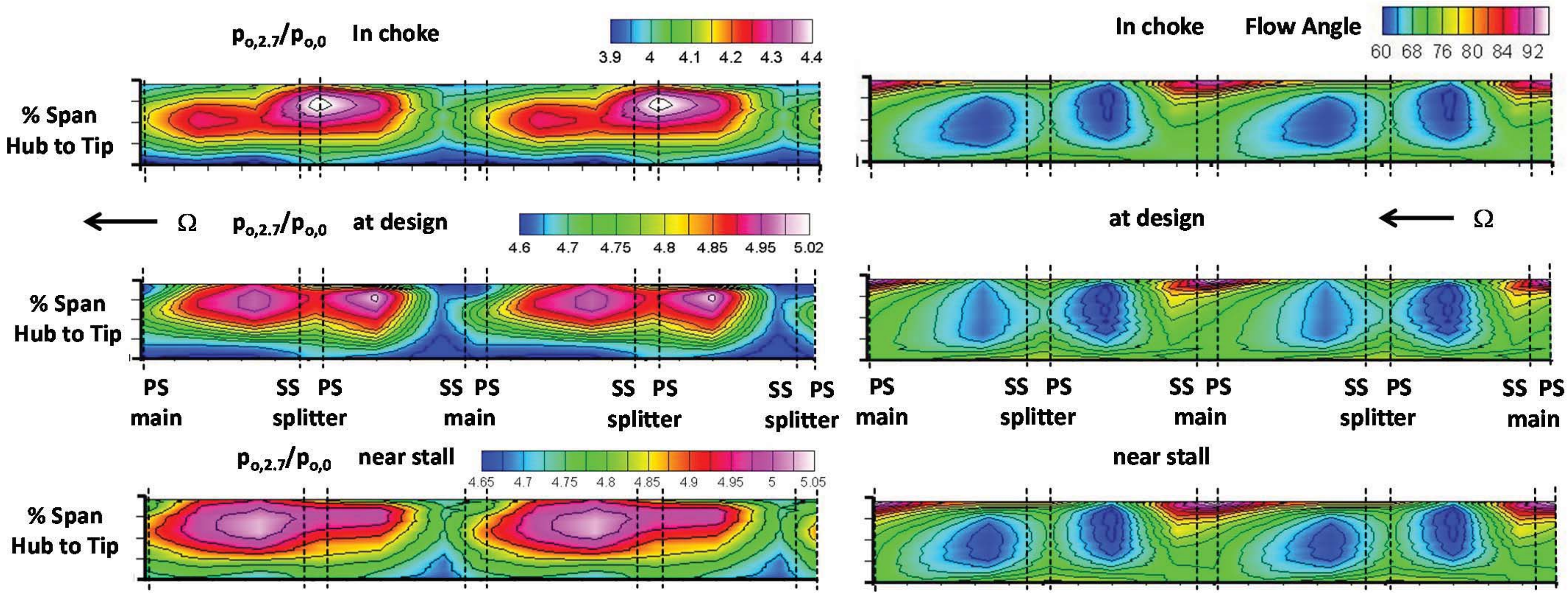
TE Mean Camber Angle

Main = 51 deg

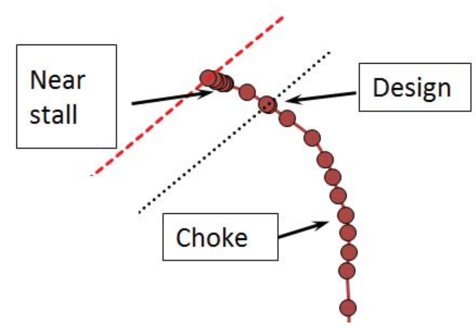
Splitter = 52 deg

← Ω

Diffuser Exit Survey Results vs. Operating Condition (N_c = 100%, Choke, Design, Near-Stall)

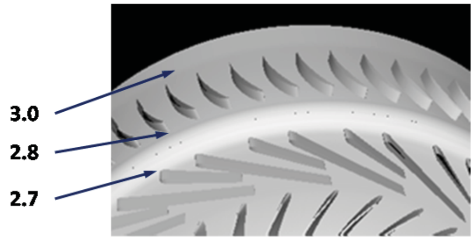


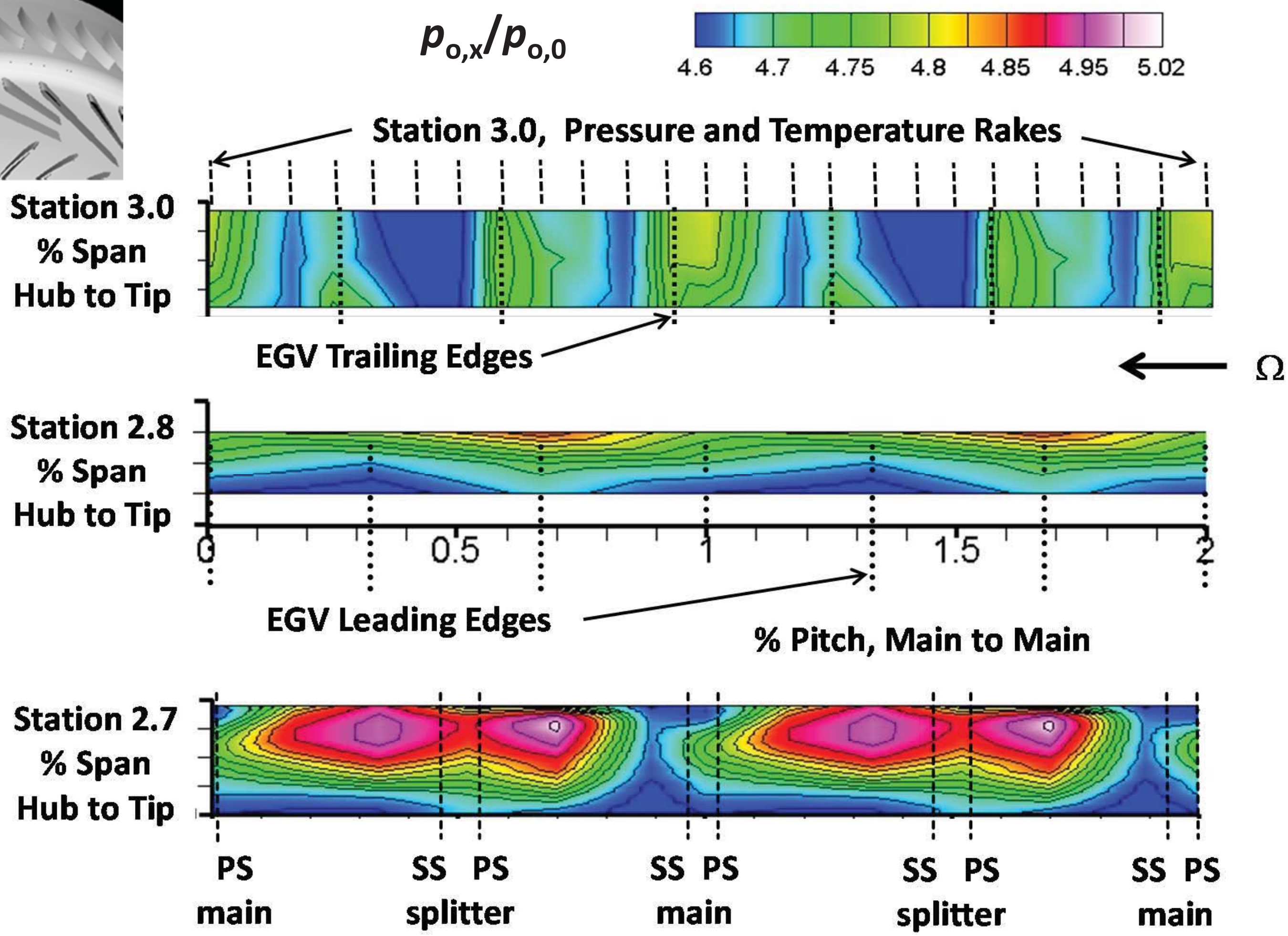
- Flow redistributes as stage is throttled
- High swirl angles at SS main vane could indicate separated flow



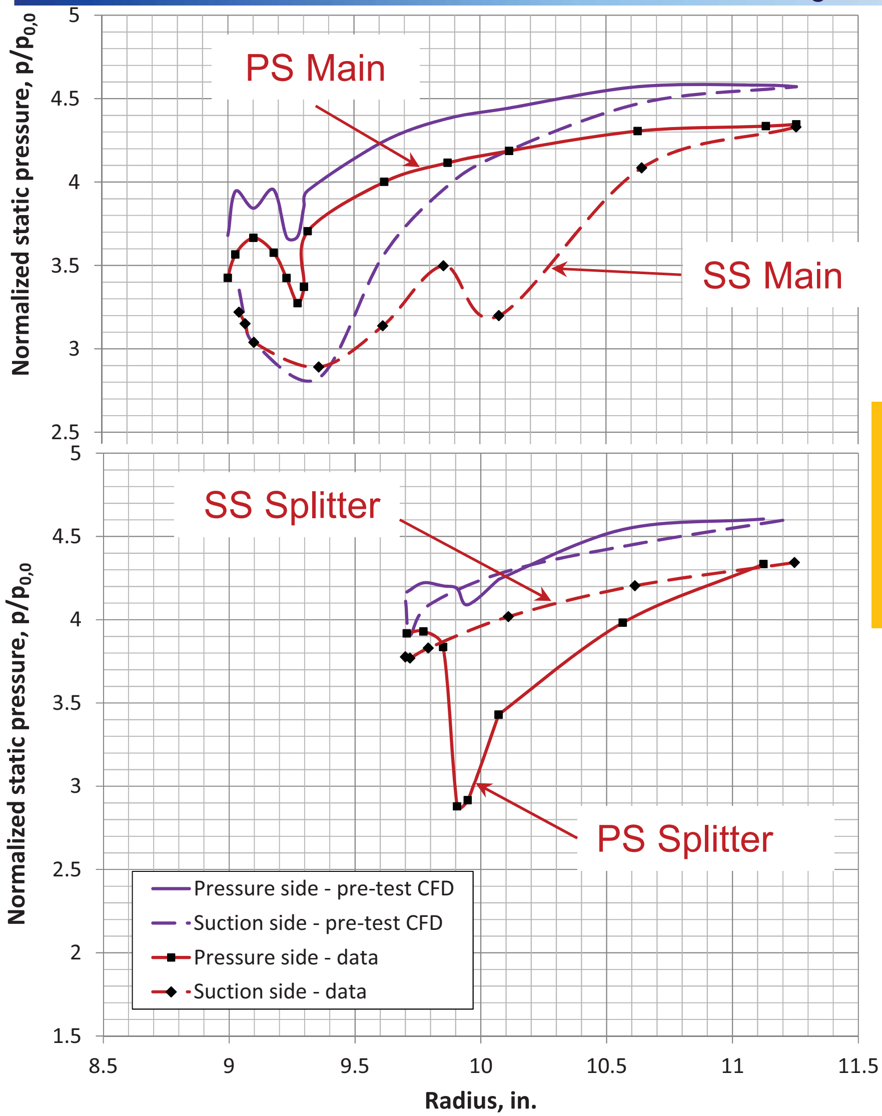
Pressure Contours at Stations 2.7, 2.8, 3.0

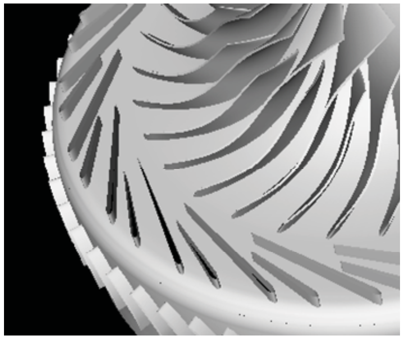
(N_c = 100%, $\dot{m}_{c,ex}$ = 3.0 lb_m/s)

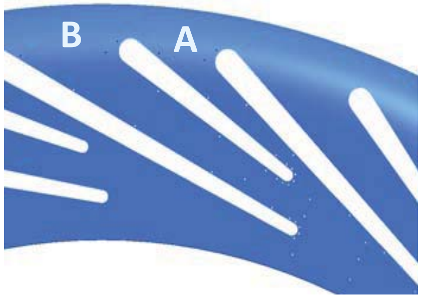




Diffuser Vanes Loading Diagrams-Shroud Static Pressures (N_c=100, near design point CFD)

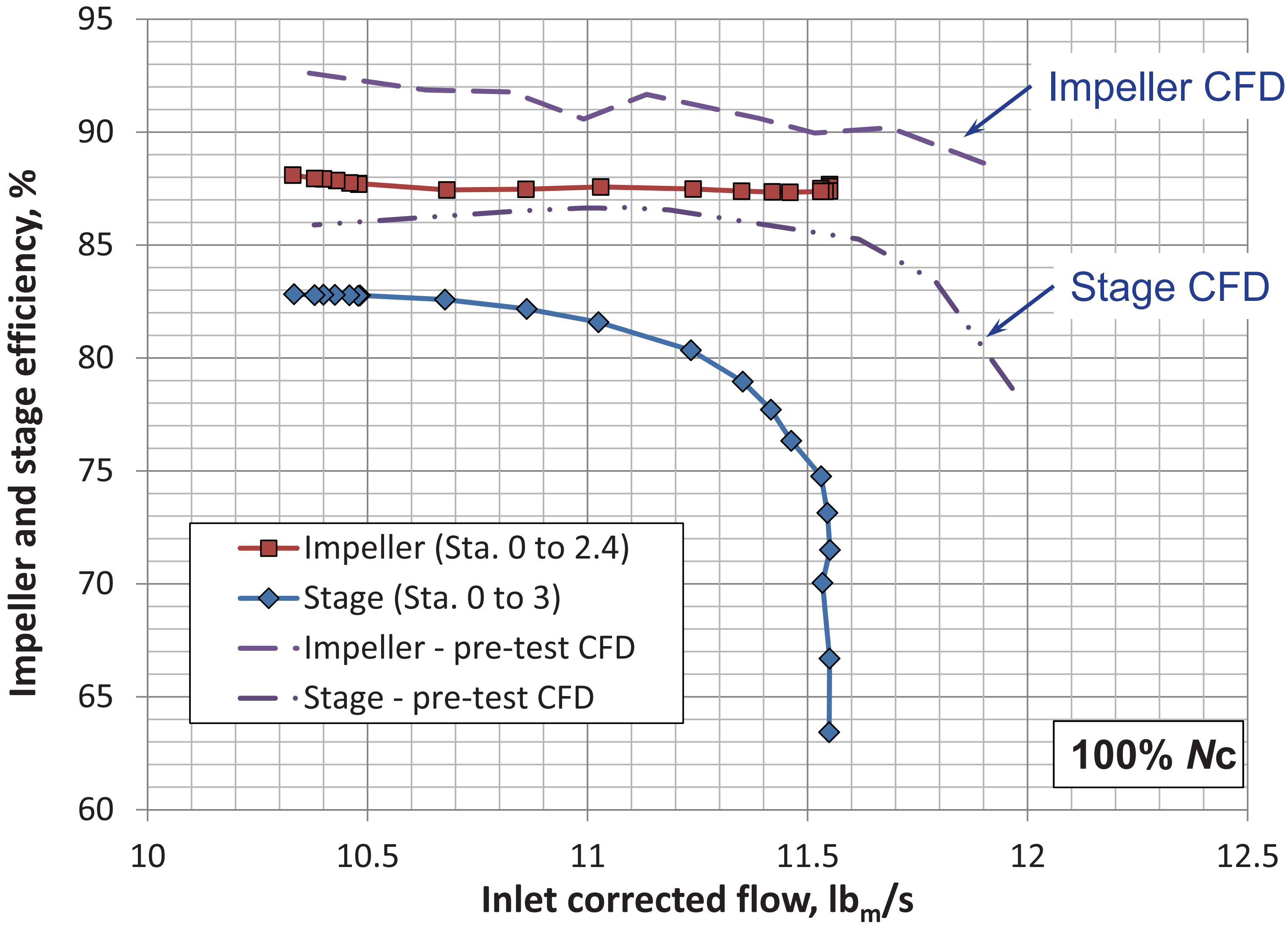






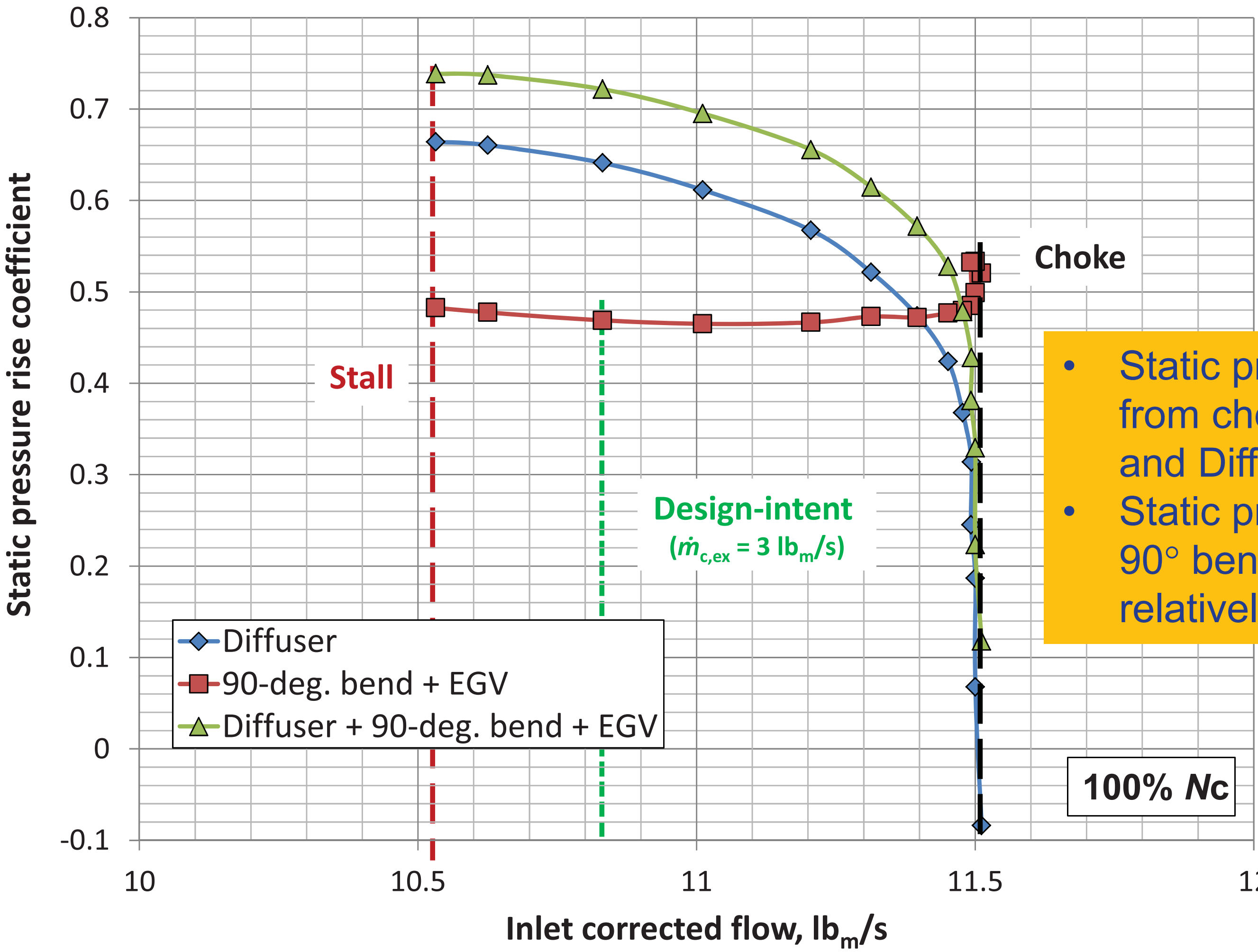
- Overall pressure rise lower than predicted
- Negative loading on splitter indicates operating at large negative incidence vs. lightly loaded design intent

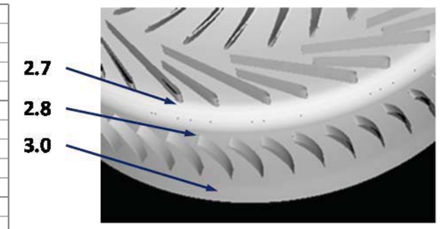
Stage and Impeller Adiabatic Efficiency



Diffusion System Static Pressure Rise

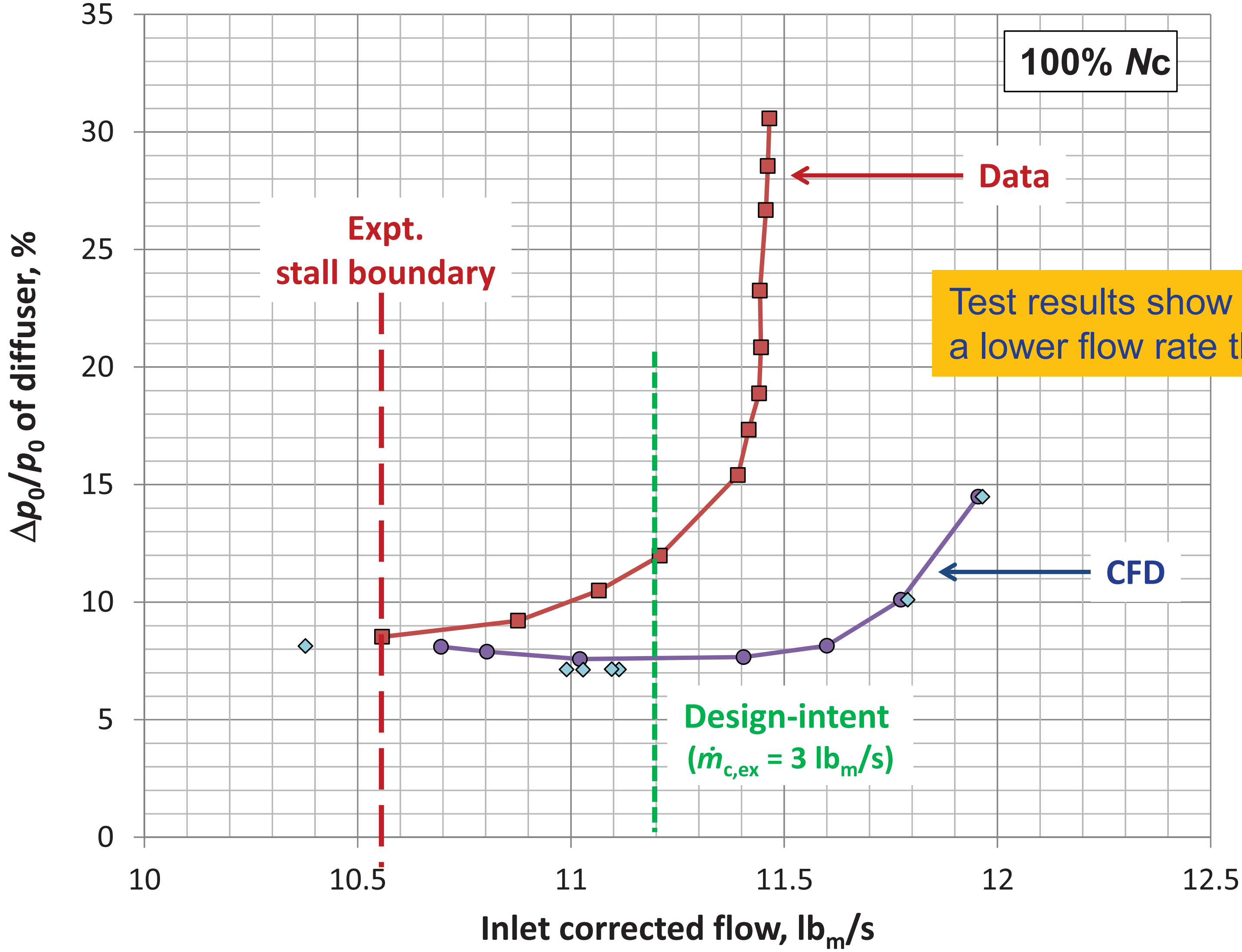
$$c_p = (\overline{p}_{ex} - \overline{p}_{in})/(\overline{p}_{0,in} - \overline{p}_{in})$$





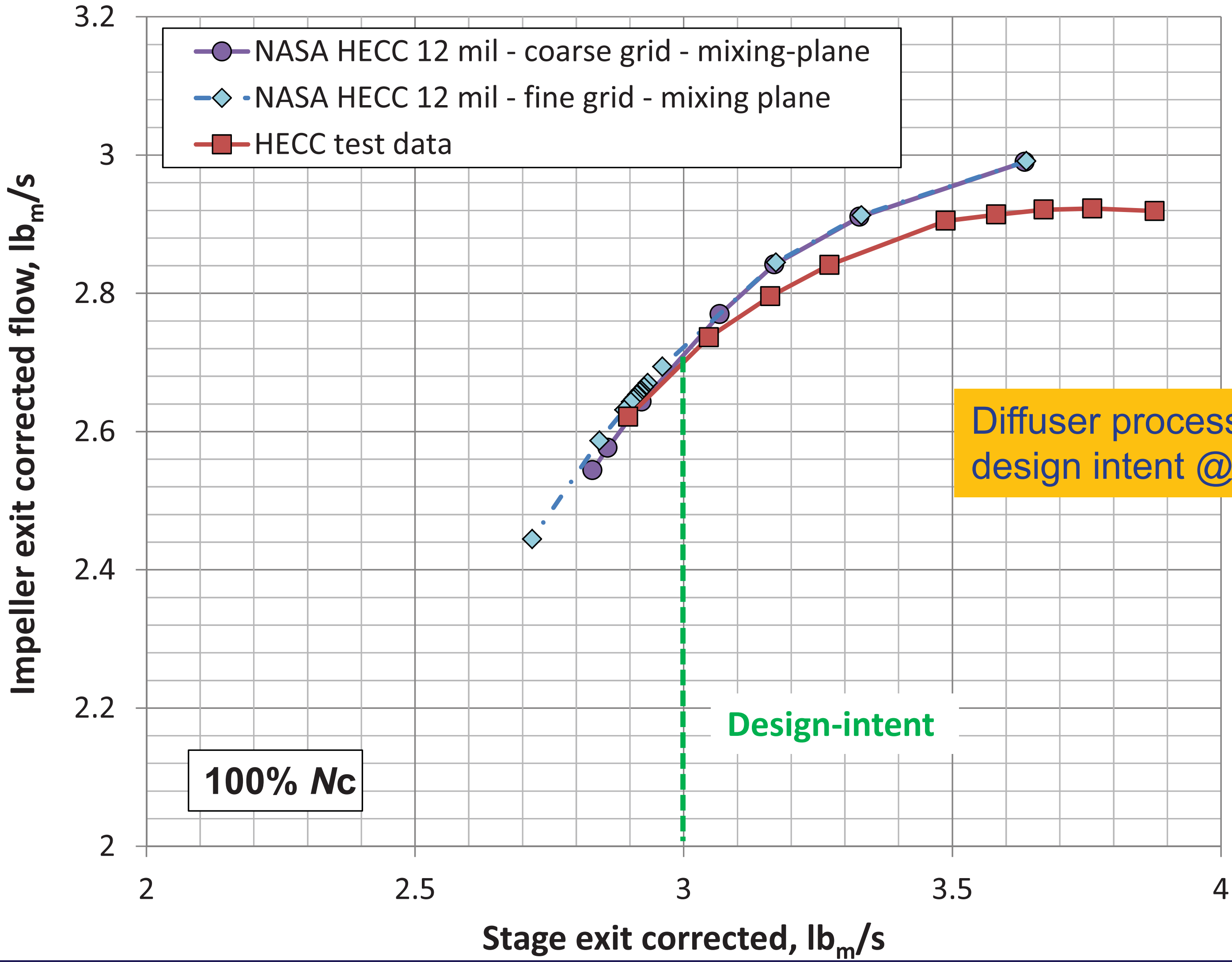
- Static pressure rise increases from choke to stall (Diffuser and Diffuser+Bend+EGV)
- Static pressure rise across 90° bend and EGV is relatively constant

Diffuser Loss Bucket



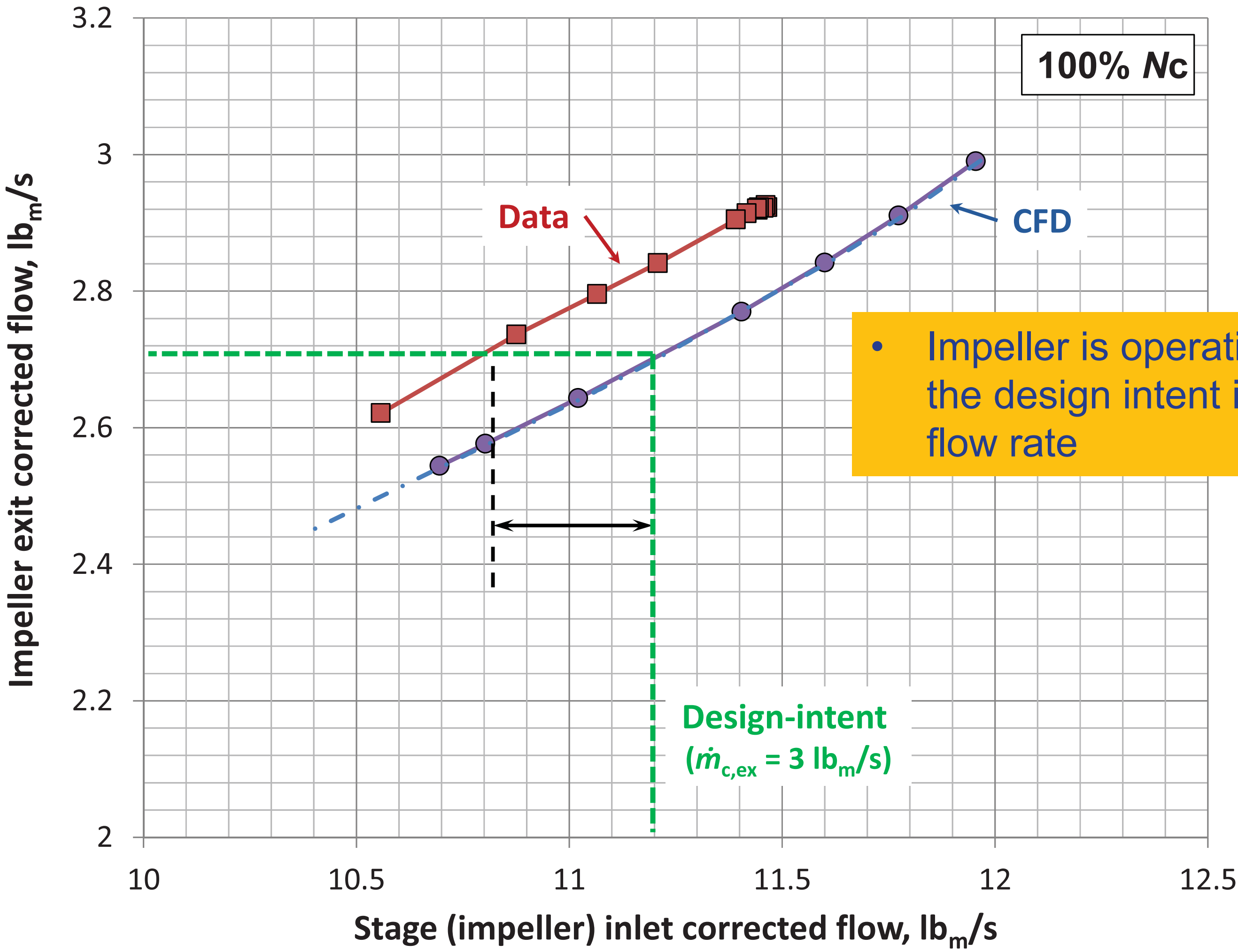
Test results show a minimum loss at a lower flow rate than design intent

Diffuser Corrected Flow Characteristic



Diffuser processes flow as per design intent @ $\dot{m}_{c,ex}$=3.0 lb_m/s

Impeller Corrected Flow Characteristic



- Impeller is operating at a lower $\dot{m}_{c,in}$ at the design intent impeller exit correct flow rate

Summary

- Aerodynamic performance of an advanced, compact, high work-factor centrifugal compressor stage was presented
- Stage performance and stability were lower than design intent
  - Adiabatic Efficiency by 2.75 pts., mass flow by 2.25%, and Stability Margin by 4.5 pts.
- Differences in predicted and measured impeller efficiency, impeller flow characteristics, and diffuser loss buckets were observed.
- Root-cause-analysis of the performance shortfall was initiated within the NRA contract. Analyses continue with intent to guide future design efforts.

Comprehensive data sets and geometry to be made publically available

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